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FIELD EXPERIMENTS ON PHYSICAL WEATHERING AND WIND EROSION IN AN ANTARCTIC COLD DESERT

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ABSTRACT

Field experiments were carried out over a five year period with the aim of understanding contemporary weathering and erosional environments in the Sør Rondane Mountains, an Antarctic cold desert region. These include observations of (1) scaling from rockwalls, (2) disintegration of tuff blocks with or without saline solutions, and (3) abrasion of artificial walls by wind. Monitoring was also made of rock surface temperature and wind speed. Despite frequent temperature oscillations across 0°C, rock scaling due to frost action was generally very slow because of low moisture content in the rockwalls. Exposure to the cold, dry climate led to the rapid disintegration of porous tuff blocks including soluble salts like halite and thenardite. This indicates that rates of weathering are increased greatly with the accumulation of such salts in the bedrock. Although gypsum did not cause any visible damage over four years, its widespread occurrence in heavily damaged rocks demonstrates that increasing gypsum contents may also intensify rock breakdown. The snow-laden katabatic wind resulted in rapid wearing of the windward face of an asbestos board with the peak erosion at 30–40 cm above the ground. Nonetheless, the landforms expected from the unidirectional wind characteristics are by no means common features because of lack of abrasive materials, such as snow and sand particles. These experiments suggest that frost weathering and wind erosion are only locally effective where plenty of moisture or an abrasive material is available, whilst salt weathering and removal of the waste by wind play a major role in constructing erosional landforms over the mountains.

KEY WORDS field experiment; weathering; wind erosion; Antarctica; cold desert

INTRODUCTION

Rocks in the inland ice-free mountains of Antarctica are exposed to one of the most severe climates on the Earth. Low temperatures and the paucity of water are unfavourable to weathering and erosional processes requiring plenty of water. As a result, the mountains are characterized by landforms common in deserts, such as tors with rock varnish, mushroom rocks, ventifacts and stone pavements (e.g. Derbyshire, 1972; Selby, 1972; Lindsay, 1973; Miotke, 1982a, b), which have modified glacial or preglacial landforms.

Weathering processes and the resulting development of soils and landforms have been extensively studied in cold deserts of Antarctica. Chemical analyses of weathered rocks and soils have produced a number of quantitative data (e.g. Kelly and Zumberge, 1961; Pastor and Bockheim, 1980; Campbell and Claridge, 1987) and have led to the modelling of the rate of soil development (Bockheim, 1980). Although these studies generally show that physical weathering is much more important than chemical weathering, there was

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usually a lack of data based on process monitoring in the field or analyses of physical properties of rocks and soils. Other important processes of physical rock comminution include wind abrasion, though this is an erosional rather than a weathering process (e.g. Ugolini, 1986).

By means of field observations and laboratory simulations, Hall (1988, 1990, 1993) has evaluated contemporary weathering processes in the maritime Antarctic, where climate is rather milder than the continental Antarctic. However, such a dynamic undertaking in the continental Antarctic is so far limited to the monitoring of rock temperatures (Miotke, 1982a; Miotke and Hodenberg, 1983; Matsuoka *et al.*, 1990) and of wind abrasion (Miotke, 1982b; Malin, 1984). During 1985–1991, a series of field experiments was undertaken in the Sør Rondane Mountains, an inland ice-free mountain area of East Dronning Maud Land. These included scaling from painted rockwalls, disintegration of porous tuff blocks initially filled with pure water or saline solutions, and the wearing of walls made of artificial materials. These experiments aimed to evaluate the effect of frost and salt weathering and of wind abrasion on the development of erosional landforms. In addition to the measurements of the rate of rock disintegration or wearing, monitoring was also made of some of the controlling factors, including rock temperature and wind speed.

THE STUDY AREA

The Sør Rondane Mountains lie about 200 km from the coast and extend about 200 km in an E–W direction. They stand up to 2000 m high above the ice sheet which itself lies at 1000 to 1500 m a.s.l. (Figure 1). Outlet

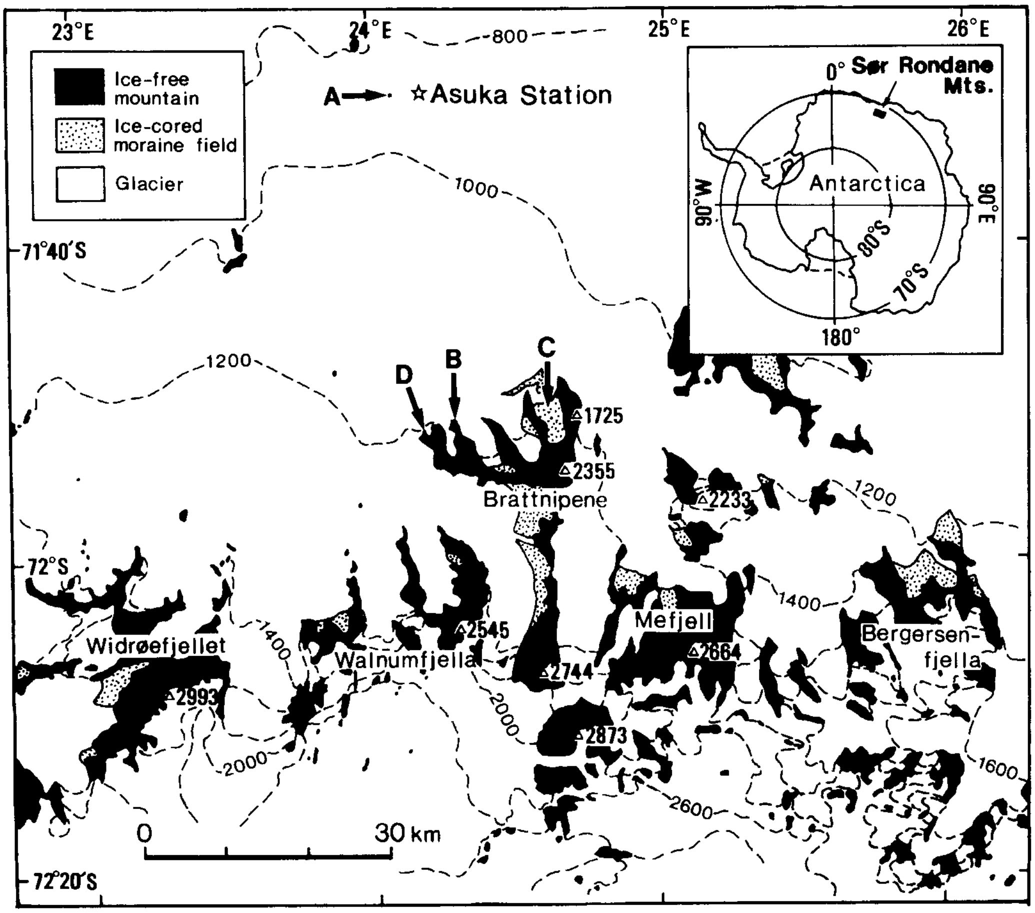

Figure 1. Map of the Sør Rondane Mountains, showing the location of the experimental sites. Contour interval 200 m

glaciers divide the mountain range into several blocks, each of which consists of a number of local glaciers and ice-free slopes. The surface of the ice-free slopes is made of bedrock, till or their weathering products. The bedrock geology is the metamorphic and plutonic rocks of Late Proterozoic to Early Palaeozoic ages (Shiraishi and Kagami, 1992). Gneiss, granite, amphibolite and diorite are most common and widespread. Syenite and tonalite are mainly exposed in the southern part of the mountain range. These rocks are intruded in places by aplite dykes.

Meteorological observations were made from 1987 to 1991 at Asuka Station, located on the snow-covered ice sheet at the northern end of the mountains (Figure 1). They show that the mean annual air temperature for five years was −18·4°C; air temperature sometimes falls below −40°C in winter, whilst rarely rising above 0°C even in mid-summer; and the ESE katabatic wind of 12·6 m s^{-1}, on the annual average, prevails throughout the year. Despite subzero air temperatures, strong sunshine in the summer daytime often causes the ground surface to thaw, generating frequent diurnal freeze–thaw cycles. The maximum depth of an active layer during a diurnal freeze–thaw cycle is 20 cm in wet soils and 40 cm in dry soils (Matsuoka *et al.*, 1990). These values define the base level for weathering processes that require water (Wellman and Wilson, 1965).

The ice-free areas are characterized by a cold desert landscape, typical of the xerous and ultraxerous zones in the Transantarctic Mountains (Campbell and Claridge, 1987). Van Autenboer (1964) first described landforms resulting from weathering and aeolian processes in the Sør Rondane Mountains, including wind-polished facets, tafoni and exfoliated rocks. The predominance of these landforms suggests that the ice-free areas are generally too dry to undergo frost action. Field monitoring indicates that frost heave and creep are activated where the soil with water content over 5 per cent by dry weight thaws deeper than 7 cm (Matsuoka and Moriwaki, 1992). Such a favourable environment has only a limited distribution, mainly depending on aspect and the prevailing wind.

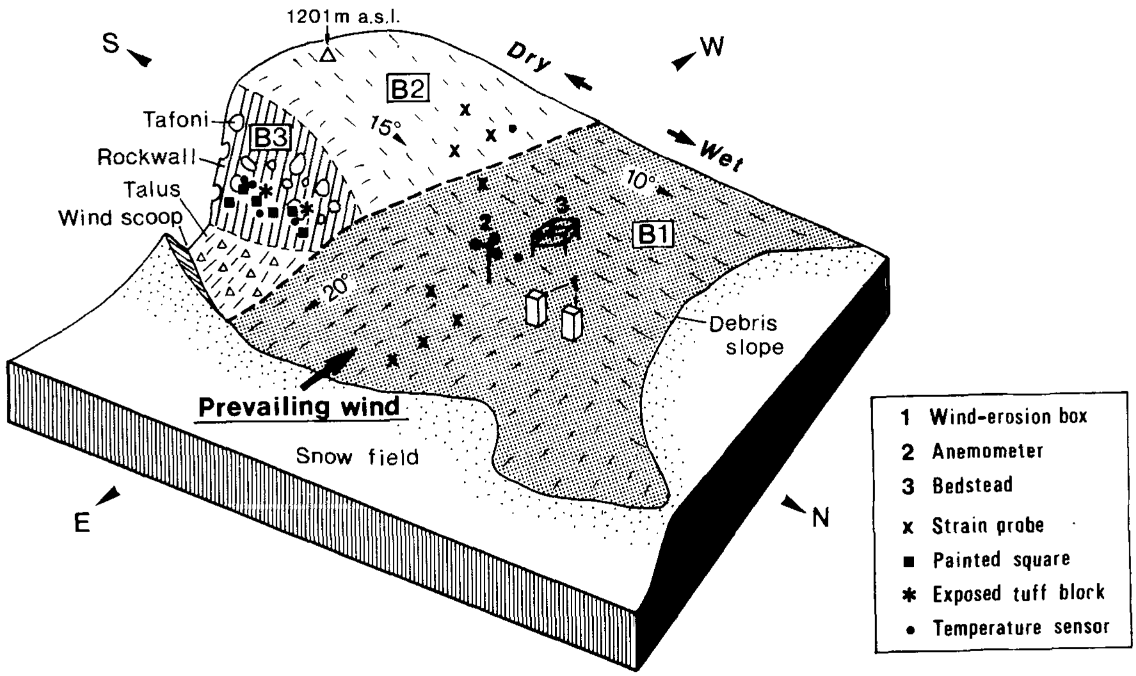

Figure 2. Schematic block diagram of Site B, illustrating the microenvironments and instrumental sites. The diagram covers an area of approximately 100 × 100 m at the northern end of a peninsular ridge. The rockwall (B3) extends to 30 m. The snow-laden wind only passes through the shaded part (B1), keeping the debris slope wet and providing an abrasive material. The bedstead and strain probes are instruments for recording frost heave and creep activities (Matsuoka and Moriwaki, 1992). The general gradients of the debris slopes are indicated

The glacial history of the Sør Rondane Mountains has been reconstructed by Hirakawa and Moriwaki (1990) and Moriwaki *et al.*, (1991, 1992). In summary, the level of the ice sheet was at a maximum during the Late Tertiary and has been lowered throughout the Quaternary with some minor fluctuations. This suggests that the ages of weathering features and soils increase, in general, with the height above the present surface of the ice sheet. This idea agrees with the field observation that landforms indicating advanced weathering, such as tors, mushroom rocks and stone pavements, mainly develop on high plateaux exposed above the ice sheet prior to a million years ago.

Field experiments were undertaken at four sites in the northern part of the Sør Rondane Mountains. Site A is located on an isolated small nunatak 2 km west of Asuka Station. Coarse-grained diorite composes a west-facing, leeward rockwall about 50 m high. The other sites (Sites B, C and D) lie along the northern margin of a large mountain mass called Brattnipene (Figure 1). Site B is located at the northern end of a peninsular ridge, part of which is usually exposed to the snow-laden easterly wind. As a result, Site B is divided in terms of microenvironments into the wet, east-facing debris slope (Site B1), dry, north-facing debris slope (Site B2), and dry, east-facing rockwall (up to 30 m high) composed mainly of biotite gneiss (Site B3); only Site B1 is subject to the snow-laden wind (Figure 2). Site C lies on a flat moraine field, probably ice-cored. Site D lies on a north-facing rockwall (*c.* 100 m high) composed of diorite. All the sites, located at an elevation between 900 m and 1200 m, experience frequent temperature oscillations across 0°C during summer (Matsuoka *et al.*, 1990). Sites A, B and C are the same as the measurement sites for slope processes (Matsuoka and Moriwaki, 1992).

EXPERIMENTS

Scaling from painted rockwalls

Contemporary rates of physical weathering were investigated by a number of methods, including measurements of (1) volumes of rockfall debris (e.g. Rapp, 1960), (2) debris dislocation from painted rockwalls

Table I. Scaling from painted squares on rockwalls

Square no.	Area (m^2)	Rock* type	Surface features†	Aspect	P-wave velocity ($km\,s^{-1}$)	Observation period (yr)	Number of freeze–thaw cycles‡ (yr^{-1})	Rate of weathering ($\times 10^{-2}\,yr^{-1}$)
Site A								
R1	0·25	DR	SJ	NW	1·6	5	na	0·00
R2	0·25	DR	SJ	SW	1·3	5	na	0·00
R3	0·25	DR	NJ	SW	2·3	5	na	0·00
R4	0·25	DR	NJ	W	2·0	5	na	0·00
Site B3								
R5	1·0	GN	T	NE	1·2	5	124	0·07
R6	1·0	GN	SJ	NE	1·5	5	145	0·09
R7	1·0	GN	DJ	NE	1·2	5	145	0·42
R8	1·0	GN	T	SE	1·4	5	78	0·32
R9	0·25	GN	DJ, SA	NE	0·5	4	145	0·00
R10	0·25	GN	H	NE	1·1	4	145	0·00
Site D								
R11	1·0	DR	NJ	NW	2·3	6	107	0·00
R12	1·0	DR	NJ	NW	2·8	6	107	0·00

* DR = diorite, GN = gneiss

† NJ = no joint, SJ = sparse joints, DJ = dense joints, T = tafoni (>ϕ20 cm), H = honeycombe structure (<ϕ20 cm), SA = salt efflorescence

‡ Records in 1986, showing effective freeze–thaw cycles defined by Matsuoka (1990a). Values from the same sensor are used for B2, B3, B5 and B6, and for D1 and D2. na = data not available

(e.g. Matsuoka, 1990a), and (3) breakage of standard rock blocks (e.g. Schumm and Chorley, 1966). The first and second methods give the weathering rate of a natural rockwall that is controlled by both environmental and geological conditions, whilst the third one allows the evaluation of environmental conditions. The second and third methods were used here.

Scaling from the natural rockwalls was measured at Sites A, B3 and D. A square of 1 or $0{\cdot}25\,m^2$ was painted on the rock surface and the ratio of the distintegrated to the originally painted area was computed from pictures taken yearly. The colour of paints was chosen according to the darkness of the rock surface to minimize albedo alteration. Painted fragments, if found beneath the squares, were collected to determine their dimensions. The squares were painted onto similar rock types (gneiss or diorite) but had different appearances. Some squares were massive and little jointed, whilst others were highly jointed or accompanied by honeycomb structures. Rock mass strength was quantitatively evaluated by longitudinal wave (P-wave) velocities propagating through the rockwalls, using a single-channel seismograph. The squares also had a wide range of the P-wave velocity values, reflecting mainly the fracture frequency (Table I).

Monitoring also includes two environmental factors presumably affecting the scaling: surface temperature and moisture content of the bedrock. Rock surface temperatures near the painted squares were monitored at 3 or 4 h intervals throughout the year with single- or multichannel recorders. Moisture contents were evaluated by collecting rock pieces, totalling about 2 kg for each site, directly from the rockwalls during freeze–thaw periods. The rock pieces were weighed in the field to determine the natural weight. The dry and saturated weights were measured in the laboratory and, using the three weight values, the degree of saturation was calculated (Matsuoka, 1990a).

Year-round, continuous data on rock temperatures were obtained at Sites B3 and D. Rock temperatures in winter displayed little diurnal variation in response to the absence of sunshine, being close to air temperatures. In summer, by contrast, the continuous daylight raised rock temperatures far above air temperatures even during the 'night' hours; besides, diurnal variations in the altitude and azimuth of the sun produced large

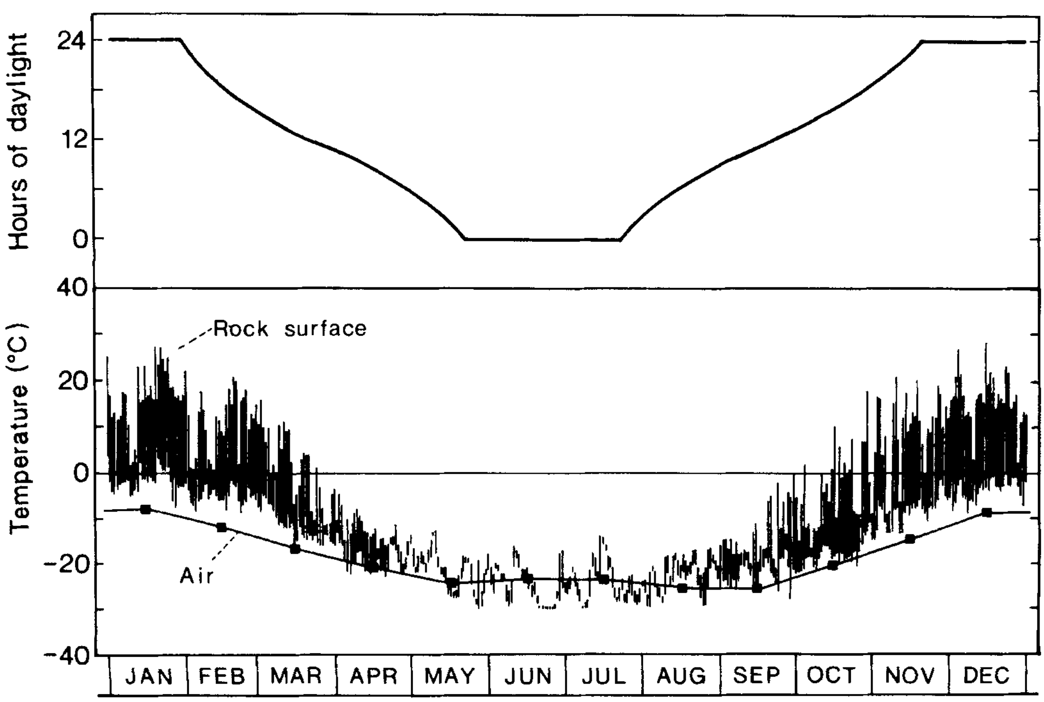

Figure 3. Annual variation in rock and air temperatures, shown with hours of daylight. The rock surface temperatures expressed by daily ranges were recorded in 1986 at Site D, the northwest-facing, warmest rockwall. Note that records are limited within ±30°C. The air temperatures indicate monthly mean values for five years (1987–1991) at Asuka Station

temperature ranges at the rock surface (Figure 3). As a result, the painted squares experienced a number of diurnal temperature oscillations across 0°C. Effective freeze–thaw cycles, counted when the rock surface temperature rises above 2°C after falling below −2°C (Matsuoka, 1990a), occurred frequently, exceeding 100 cycles per annum on most of the rockwalls (Table I). The high daytime temperatures in summer indicate that the freeze–thaw frequency is also high on the upland ice-free areas; for example, about 100 cycles per annum are expected to occur on the mountains 1000 m above the ice sheet, where rock temperatures are presumably 5–10°C lower than the experimental sites (see Figure 3).

Although the freeze–thaw frequencies were considerably higher than those on the rockwalls in the Japanese Alps and in Svalbard, the bedrock shattering rates, less than 1 per cent per annum (Table I), were much lower than the values in the other two regions (Matsuoka, 1991). The low weathering rates probably resulted from the low moisture content of the bedrock, being usually 30–40 per cent saturated (Table II). Laboratory experiments showed that frost weathering is insignificant unless either the degree of saturation exceeds 70–80 per cent before freezing, or the water table is close enough to supply moisture towards the freezing front (Matsuoka, 1990b). Most of the rockwalls in the Sør Rondane Mountains do not often achieve these moisture criteria, and hence rarely undergo intensive frost weathering.

Dislocation happened mainly along joints in the densely fractured bedrock (R7) or as flaking on the side-wall of tafoni (R5, R8). The fallen fragments were mostly smaller than 3 cm in the long axis, with the maximum fragment having dimensions of 22 × 7 × 5 cm. The scarcity of large debris can be attributed to the absence of long-term thawing that penetrates deeper than many tens of centimetres (cf. Matsuoka, 1994). The sizes of the fragments are much smaller than those in many other cold regions with deep seasonal freeze–thaw, such as northern Scandinavia (Rapp, 1960) and Baffin Island (Church *et al.*, 1979).

Disintegration of porous tuff blocks

The effect of salt action was evaluated by the exposure of standard rock blocks to the field conditions, as done by Goudie and Watson (1984). Cubic blocks of porous welded tuff with dimensions of 5 × 5 × 5 cm were prepared for this experiment. The geotechnical properties of the tuff are porosity of 39·3 per cent, dry bulk density of 1·47 g cm^{-3}, specific surface area of 17·5 m^2 g^{-1}, and tensile strength of 0·78 MPa. The tuff is much more porous and weak than the gneiss in the Sør Rondane Mountains, with an average porosity of 1·4 per cent and tensile strength of 5·4 MPa, and hence is expected to be highly susceptible to physical weathering. In fact, laboratory tests show that the saturated tuff specimens are completely broken down during five to ten freeze–thaw cycles (Matsuoka, 1990b). Before exposure, the rock blocks were submerged in pure water or saturated saline solution of halite (NaCl), thenardite (Na_2SO_4) or gypsum ($CaSO_4.2H_2O$) for a week. The treated blocks were placed directly on the moraine field (Site C) and on ledges of the rock-walls (Sites A, B3 and D), where moisture supply appears to be extremely limited; thus, despite being initially saturated, the blocks would have dried within a few days to balance with the humidity of air. The experiment was started during the austral summer of 1985/86 (blocks with pure water) or 1986/87 (blocks with saline solutions). The damage to the blocks was checked during the summers of 1986/87, 1987/88 and 1990/91.

After four to five years, visible breakage rarely appeared on the blocks with pure water and gypsum solution (Table III). The soundness of the blocks with pure water indicates, again, inefficient frost weather-ing because of the lack of moisture. By contrast, the blocks with thenardite were significantly cracked and

Table II. Moisture contents of rock samples during freeze–thaw periods

Location	Degree of saturation (%) (sampling date)	
Site A	32·7 (4 Jan. 86)	32·4 (22 Dec. 86)
Site B3	32·2 (7 Jan. 86)	37·2 (10 Jan. 87)
Site D	37·2 (10 Jan. 87)	

Table III. Disintegration of exposed porous tuff blocks (5 × 5 × 5 cm) with or without saline solutions

Solution	Number of samples	Observation period (yr)	Change in sample appearance
Pure water	7	5	Little breakage after 5 years.
$CaSO_4$	3	4	Little breakage after 4 years.
Na_2SO_4	3	4	Visible cracks after 1 year, and significantly cracked and rounded after 4 years.
NaCl	3	4	Significantly cracked after 1 year, and completely disintegrated after 4 years.

rounded, and those with halite were almost completely broken down during the same period (Figure 4a). This demonstrates that fluctuation in humidity allows halite and thenardite to dissolve and recrystallize repeatedly, yielding significant rock damage even in this low temperature environment.

Laboratory experiments show that the ranking of the power of salts is such that thenardite $\gg$ halite > gypsum (Kwaad, 1970; Goudie, 1985, 1986), which is inconsistent with the present case showing that halite > thenardite $\gg$ gypsum. Theoretically, however, for a given temperature or supersaturation level halite can exert the largest crystallization pressure among these salts (Winkler and Singer, 1972). The inconsistency of the ranking between the laboratory experiments and cold environment results may have originated from differences in temperature or humidity conditions.

Abrasion of vertical walls made of artificial materials

Wind abrasion may also be effective in comminuting rocks. Evidence for wind abrasion in Antarctica has been indicated by the widespread occurrence of ventifacts (e.g. Lindsay, 1973) and by field and laboratory experiments (Miotke, 1982b; Malin, 1984). In the Sør Rondane Mountains, small ventifacts with polished and/or etched surfaces are also common features on the high plateaux exposed prior to a million years ago (Moriwaki *et al.*, 1991).

Vertical velocity profiles of wind abrasion were evaluated through wearing of a board (100 cm high, 40 cm wide and 1 cm thick) made of two kinds of artificial materials: asbestos cemented with gypsum and polyvinyl chloride (PVC). The asbestos board (*c.* 2 on Mohs' hardness scale) is much softer than the bedrock (hardness

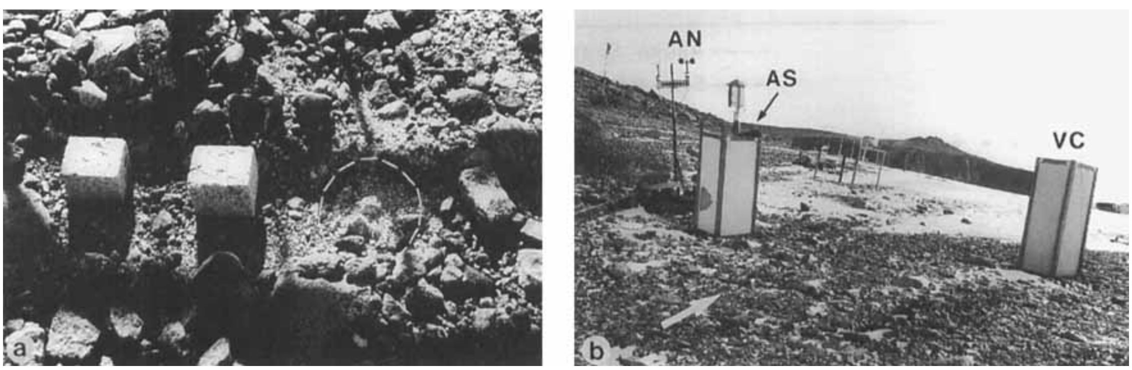

Figure 4. The field experiments. (a) Disintegration of tuff blocks (5 × 5 × 5 cm) at Site C over a four year period. The block was damaged very little by $CaSo_4.2H_2O$ (left), was considerably cracked by Na_2SO_4 (centre) and completely fragmented by NaCl (right, enclosed with the broken circle). (b) Abrasion of the vertical walls at Site B1 over a two year period. The windward face of the 1 cm thick asbestos board (AS) was intensively worn to form a hole at 30–40 cm above the ground, whilst no face of the 1 cm thick PVC board (VC) showed visible erosion. Wind speeds were recorded with the anemometer (AN) connected to a data logger. The white arrow indicates the prevailing wind direction

between 5 and 7). By contrast, the PVC board has only slightly less strength (compressive strength 60–90 MPa) than the bedrock in the Sør Rondane Mountains (110–150 MPa), hence approximating the wearing rate of the real rocks. Four boards of the same material were combined to make a box, and the two kinds of boxes were placed at Sites B1 and C during the summer of 1986/87. One side of each box faced the prevailing wind. Wear of the boards was measured after one, two and four years from the initial setting. Wind speed at 1·5 m above the ground was also monitored at Site B1 (Figure 4b). A data logger recorded the mean speeds at 10 min intervals from 31 December 1988 to 26 January 1989, and thereafter at 90 min intervals until 16 January 1990.

Wind data at Site B1 show that the mean annual wind speed in 1989 was 6 m s^{-1} and that the speed sometimes exceeded 20 m s^{-1} (Figure 5a). The temporal variation in speed was parallel with that at Asuka Station. Much weaker winds at Site B1 may have resulted from the blocking effect of the mountain mass of Brattnipene, or simply from the lower position of the anemometer. Year-round data on wind direction were not available at Site B1, but observations during summer indicated that the dominant direction is E rather than ESE as at Asuka Station (Figure 5b). The ESE katabatic wind may be curved somewhat by the mountain mass before approaching Site B1.

No measurable abrasion occurred on either the asbestos or PVC board at Site C in four years. The windward face of the asbestos board became rough but wearing never exceeded 1 mm. In Site B1, the windward face of the PVC board was only slightly scratched, whilst that of the asbestos board suffered significant erosion. After a year from the initial setting, the windward face of the asbestos board was worn by at most 2 mm; after two years the maximum wear exceeded 10 mm and, accordingly, a hole appeared (Figures 4b and 6). Abrasion was maximized at 30–40 cm above the ground. Such a profile is similar to the theoretical profile of kinetic energy flux for saltation (Anderson, 1986). It is worth remarking that the abrasion rate of the asbestos board overestimates greatly the rate for the real rocks. The negligible erosion of the PVC board indicates that, even on the windward face, the bedrock is rarely worn within a few years.

The abrasive agent here must be snow particles, because Site B1 faces a large snow field from which a snow-laden wind blows constantly. Sand particles are rarely transported. This assumption is supported by the invisible abrasion of the windward asbestos board at Site C, where the wind rarely carries snow particles. The laboratory experiment by Dietrich (1977) shows that snow-laden winds with moderate speeds of 6–10 m s^{-1} can abrade rocks at temperatures between −10 and −25°C. Thus the wind conditions at Site B1 are such that the bedrock is worn considerably over a long period, though two other factors, concentration and hardness of snow particles, must also be taken into account.

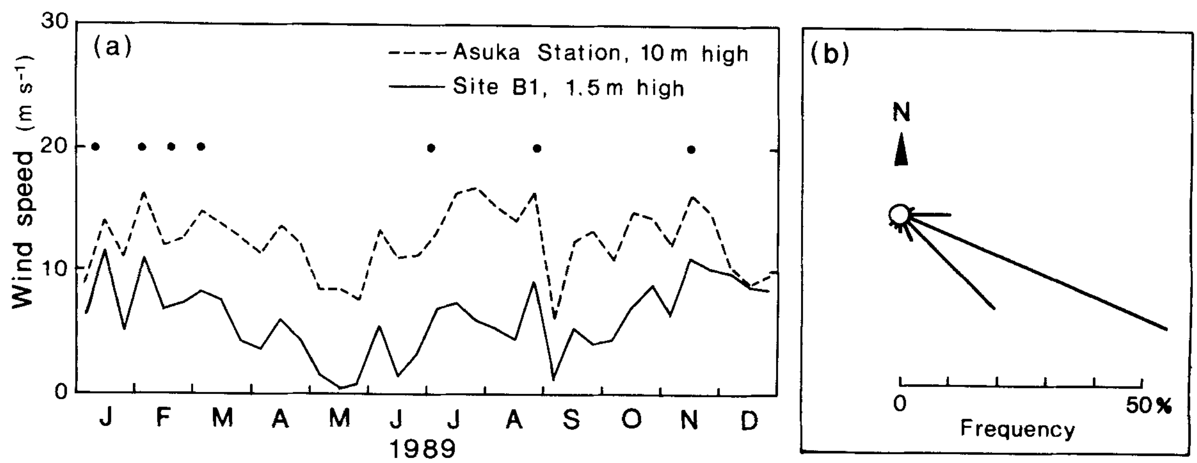

Figure 5. Wind speeds and directions in 1989. (a) Ten day mean wind speeds at Asuka Station and Site B1. The circles indicate that 90 min mean speed at Site B1 exceeded 20 m s^{-1}. (b) Wind rose in 1989 at Asuka Station. Data at Asuka Station are based on Meshida *et al.* (1990)

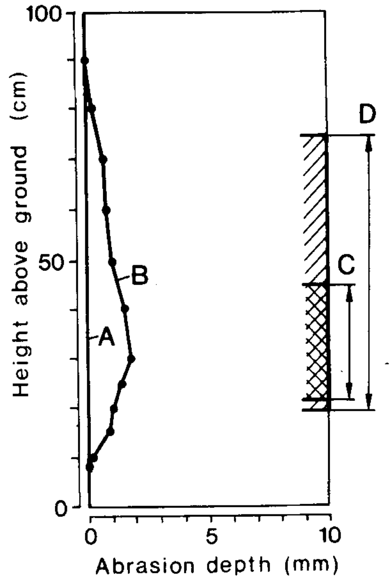

Figure 6. Abrasion of the windward asbestos board at Site B1: A = initial state (11 Jan. 1987); B = maximum depth after one year (31 Dec. 1987); C = vertical extent of a hole after two years (30 Dec. 1988); D = vertical extent of a hole after three years (14 Mar. 1990)

The profile of abrasion after a year (Figure 6) is similar to that recorded in areas with intense saltation of mineral particles where the peak erosion is recorded at 10–30 cm above the ground (e.g. Sharp, 1964; Malin, 1984; Anderson, 1986). The slight difference in the height of peak erosion may result from the type of abrasive particle: light snow can presumably saltate higher than sand.

IMPLICATIONS FOR CONTEMPORARY WEATHERING ENVIRONMENTS AND LANDFORMS

Frost weathering

The two experiments on physical weathering demonstrate that the arid climate dominating over the Sør Rondane Mountains is generally unfavourable to frost weathering. Where plenty of moisture is locally available, however, high frequency of temperature oscillations across 0°C would activate frost weathering, destabilizing the bedrock. Such a high humidity seems to be achieved in the following situations (Figure 7). First, a rockwall adjacent to a snow field and subject to a snow-laden wind frequently receives water that on thawing infiltrates rock fissures; the subsequent freezing may enlarge the fissures. In fact, ice-filled joints and significant rock breakage along the joints are observed on some east-facing rockwalls in contact with large snow fields. Frost heave and creep activities recorded at Site B1 (Matsuoka and Moriwaki, 1992) also demonstrate the possible efficacy of frost weathering in such a location.

Secondly, intensively shattered rocks are often observed around frozen ponds on undulating, ice-cored moraine fields (Figure 8a). The most plausible explanation for this is that during summer daytime, ice melting on the periphery of the ponds provides water to rock blocks, resulting in the rock breakdown on subsequent freezing. Finally, high moisture is also achieved in ice-cored tills thinner than 20 cm. Through the thin debris layer, the thawing front sometimes penetrates the underlying ice, produced meltwater that moistens the debris layer. Refreezing of the moist layer may be accompanied by the shattering of stones in the till. Intensive frost action in the third type-location is also suggested by small sorted circles which often develop on thin clay-rich tills. These humid environments occur mainly near the ice sheet level. They are unlikely to occur on the old, upland ice-free areas where, despite high freeze–thaw frequency being expected, the source of moisture is restricted.

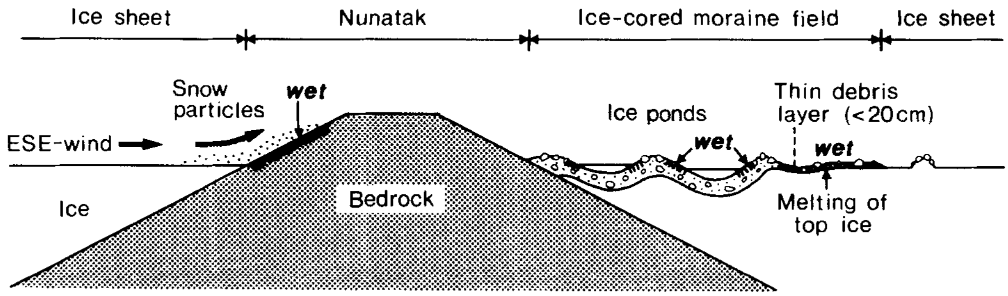

Figure 7. Locations of humid environments adjacent to the ice sheet surface

Salt weathering

Evidence for salt weathering is given by exfoliation or granular disintegration of rocks with salt efflorescence (Figure 8b). Rock joints filled with salts are also indicative of the joint separation due to salt segregation. Salts accompanying such damaged rocks were collected from about 40 locations in the mountains and identified by X-ray diffraction (XRD) with Ni-filtered Cu Kα radiation. XRD indicated that most of the samples contain gypsum, represented by the major peak at 7·6 Å, or $2\theta = 11{\cdot}7°$ (Figure 9a), and some contain other sulphates, such as thenardite, epsomite ($MgSO_4.7H_2O$), bloedite ($Na_2SO_4.MgSO_4.4H_2O$) and jarosite [$KFe_3(SO_4)_2(OH)_6$] (Matsuoka, 1995).

Another possible indicator of salt weathering is tafoni (e.g. Prebble, 1967; Bradley *et al.*, 1978), which are widespread over the Sør Rondane Mountains. A number of tafoni appear to be developing, as indicated by flaking on their ceilings and sidewalls, despite not necessarily being accompanied by visible salts. Flakes without visible efflorescence were sampled at eight tafoni and analysed by XRD. Irrespective of rock types, samples from six tafoni displayed traces of gypsum among the peaks of the original minerals (Figure 9b), supporting the idea that salt weathering is responsible for the development of the tafoni. The scaling in the painted tafoni (R5, R8) over the five years may have resulted from salt weathering.

These observations demonstrating the efficacy of gypsum contradict both the previous laboratory and present field experiments in which gypsum is shown to cause little rock breakage. This appears to arise from the low solubility of gypsum, which only allows small amounts of crystals to segregate from evaporating saturated solution of $CaSO_4$ (Kwaad, 1970). Theoretical studies show that both crystallization and hydration pressures of gypsum are very high (Winkler and Wilhelm, 1970; Winkler and Singer, 1972). Thus, if

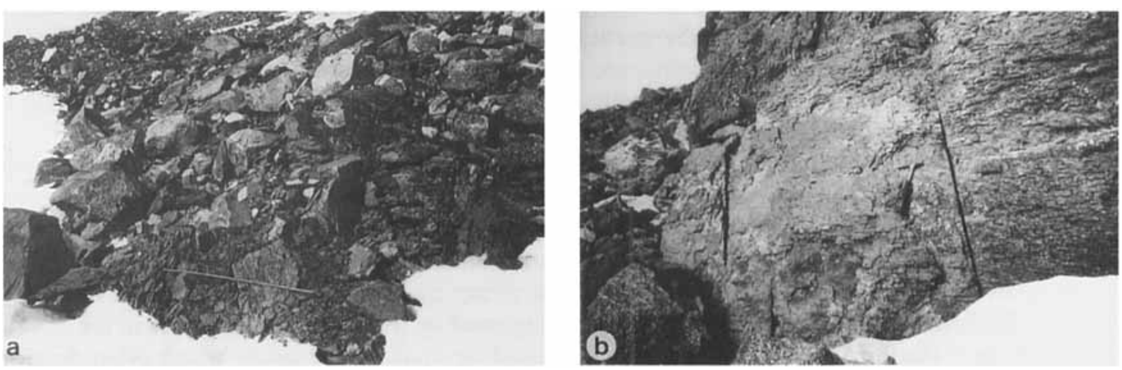

Figure 8. Physically damaged rocks. (a) Intensive disintegration of moraine gravel (mainly biotite gneiss) along a frozen pond. These rocks are wet and do not contain any soluble salts. The scale is 1 m long. (b) Damaged rockwall made of syanite. Gypsum efflorescence partly covers the rock surface (for example, the white part above the 32 cm long hammer) and fills the fractures

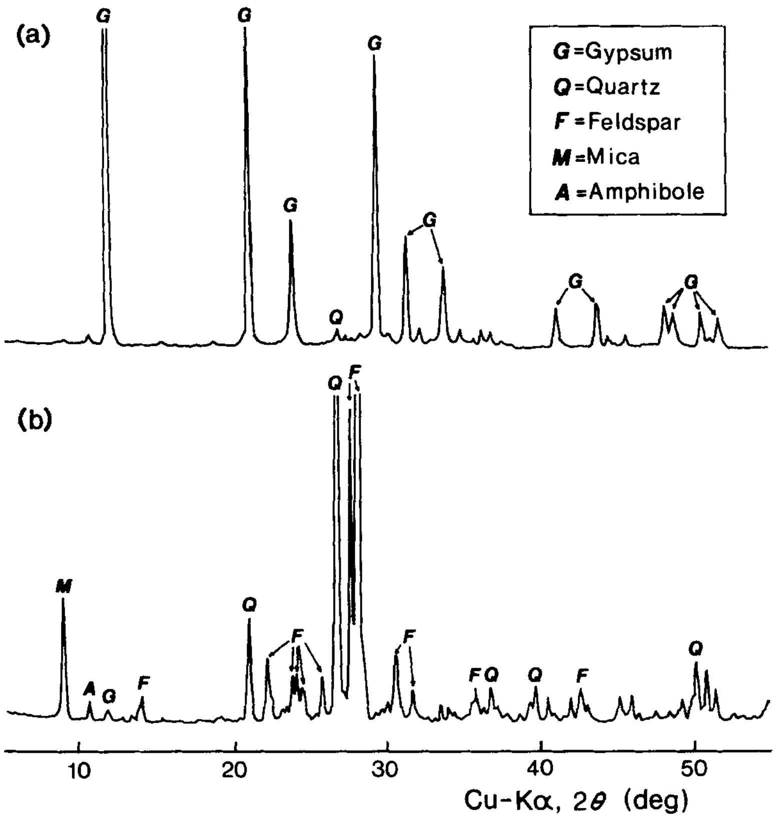

Figure 9. Typical X-ray diffractograms of (a) a salt efflorescence on a damaged rockwall (Figure 8b) and (b) flaking rock debris within a tafone made of diorite

the gypsum content is greatly increased in rocks through the long-term repetition of wetting and drying, crystallization or hydration would eventually result in the rock breakdown. Observations show that stone structures with a high gypsum content, such as the Sphinx of Egypt, the Acropolis of Athens and a museum in Chicago, suffer great damage (Gauri, 1990), and also demonstrate that gypsum is responsible for the rock breakdown, although the speed of breakdown may be much lower than that caused by some other salts.

Other sulphates, including thenardite, epsomite and bloedite, all of which are ranked as powerful salts (e.g. Goudie, 1986), mainly occur on the high plateaux as a filling of rock joints, or as a distinct horizon or small patches in old soils underlying stone pavements. The accumulation of these salts in near-surface layers is believed to contribute to rock fragmentation and soil development. Halite, the most powerful of the three experimental salts, is almost absent in these inland mountains (Matsuoka, 1995), probably because the katabatic wind prohibits landward intrusion of sea salts.

Wind erosion

Since the wind is virtually unidirectional, the result of the wind erosion experiment suggests that abrasion by the snow-laden wind eventually produces cavities at the foot of rockwalls facing the prevailing wind, or tors with an asymmetrical profile. Nonetheless, such basal cavities on windward rockwalls or asymmetrical tors are by no means common features, indicating that wind abrasion is generally very slow. This may result from the paucity of abrasive materials. Not only snow but also sand particles act on limited areas in the Sør Rondane Mountains, as there is no sand dune field from which a large quantity of sand is derived. The exclusive occurrence of ventifacts on the old high plateaux may partly result from high wind speeds, but can also

be attributed to slow abrasion due to lack of an abrasive material. Consequently, the role of wind abrasion is only a slightly modifying factor in the shape of rockwalls or stones created by other physical processes. Wind is probably much more important as the transporter of fine materials produced by rock weathering.

CONCLUSIONS

Contemporary physical weathering and erosional processes in the Sør Rondane Mountains, an Antartic cold desert region, were evaluated through field experiments over a five year period. The experiments include observations of (1) scaling from rockwalls, (2) disintegration of tuff blocks with or without saline solutions, and (3) abrasion of artificial walls by wind, and have led to the following conclusions.

Despite frequent temperature oscillations across 0°C, scaling from painted rockwalls due to frost action was generally very slow because of low moisture content in the rockwalls. Frost weathering may operate only where plenty of moisture is provided by a snow-laden wind or ice melting. By contrast, the exposure of porous tuff blocks to a cold, dry climate showed that rocks including soluble salts like halite and thenardite distingegrated rapidly, indicating that the rate of weathering is greatly increased with the accumulation of such salts. Although gypsum did not cause any visible damage to the blocks over four years, its widespread occurrence in the heavily damaged bedrock or in scaled fragments within tafoni demonstrates that increasing gypsum content may also intensify rock breakdown. The abrasion of an asbestos board facing the snow-laden katabatic wind suggests that snow particles can polish the windward face of rockwalls, with the peak erosion at 30–40 cm above the ground. Nonetheless, landforms expected from the unidirectional wind characteristics, such as cavities at the base of rockwalls and asymmetric tors, are uncommon because there is generally a paucity of abrasive materials, suggesting that wind abrasion is by no means a dominant geomorphic process. Consequently, frost weathering and wind erosion are considered only locally effective where plenty of moisture or an abrasive material is available, whilst salt weathering and removal of the weathering products by wind play a major role in constructing erosional landforms over the mountains.

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